Coming Attractions in Particle Physics

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- Neutrino Puzzles
- The World's Most Powerful Microscope
- What Can We Learn from the Top Quark?
- Is Nature Supersymmetric?
- How Many Dimensions to Spacetime?

$$\nu$$

Neutrinos . . .

- are tiny subatomic particles
- carry no electric charge
- have (almost) no mass; move (nearly) at the speed of light
- hardly interact at all

ν

Neutrinos are among the most abundant particles in the Universe

- Inside your body are more than 10 million (10^7) neutrinos left over from the Big Bang.
- Each second, some 10^{14} neutrinos made in the Sun pass through your body.
- Each second, about a thousand neutrinos made in Earth's atmosphere by cosmic rays pass through your body.
- Other neutrinos reach us from natural (radioactive decays of elements inside the Earth) and artificial (nuclear reactors) sources.

Our awareness of neutrinos

Started with a puzzle in 1913 . . .

That led to an idea in 1930 . . .

That was confirmed by an experiment in 1953.

Today, neutrinos have become

An important tool for particle physics and astrophysics . . .

Fascinating objects of study that may yield
important new clues about the basic laws of nature.

The Puzzle

Natural (and Artificial) Radioactivity includes Beta (β) Decay,

$$^{A}\mathrm{Z} \to \; ^{A}(\mathrm{Z}+1) + \beta^{-} \; ,$$

where β^{-} is the old-fashioned name for an electron.

Examples are tritium β decay,

$$^{3}\mathrm{H}_{1} \to \; ^{3}\mathrm{He}_{2} + \beta^{-} \; ,$$

neutron β decay,

$$n \to p + \beta^{-} \; ,$$

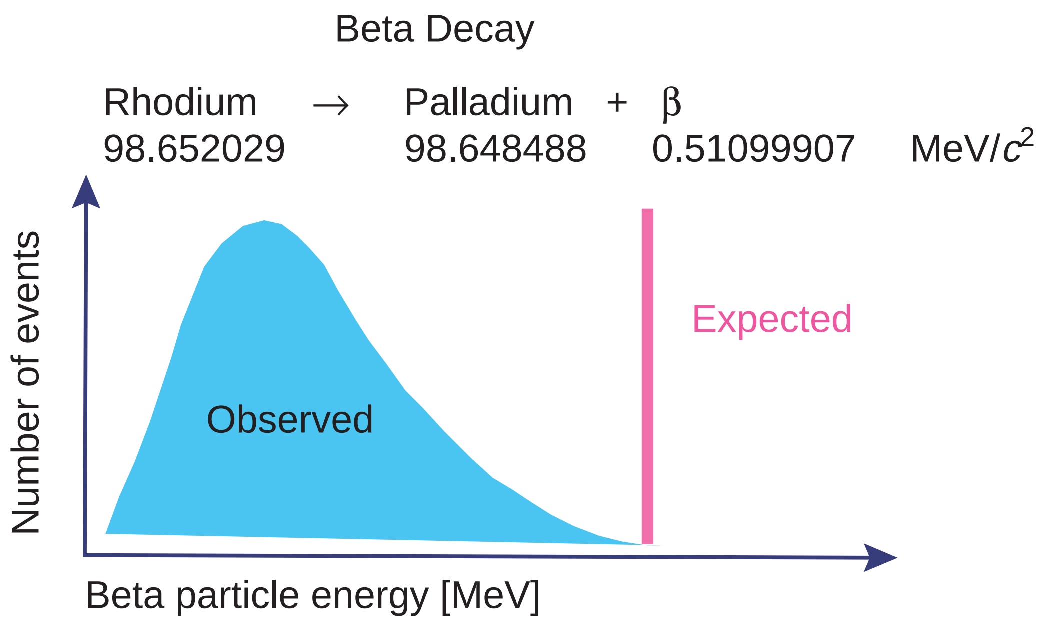
and β decay of Rhodium–106,

$$^{106}\mathrm{Rh}_{45} \to \; ^{106}\mathrm{Pd}_{46} + \beta^{-} \; .$$

For such two-body decays, the Principle of Conservation of Energy & Momentum says that

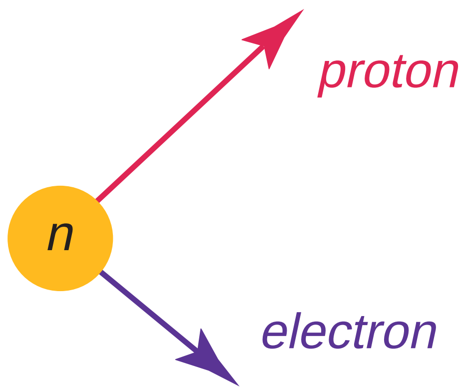
the β particle should have a definite energy.

In 1913, James Chadwick (later to discover the neutron) observed that the electron energy has a continuous spectrum.



Is energy not conserved?

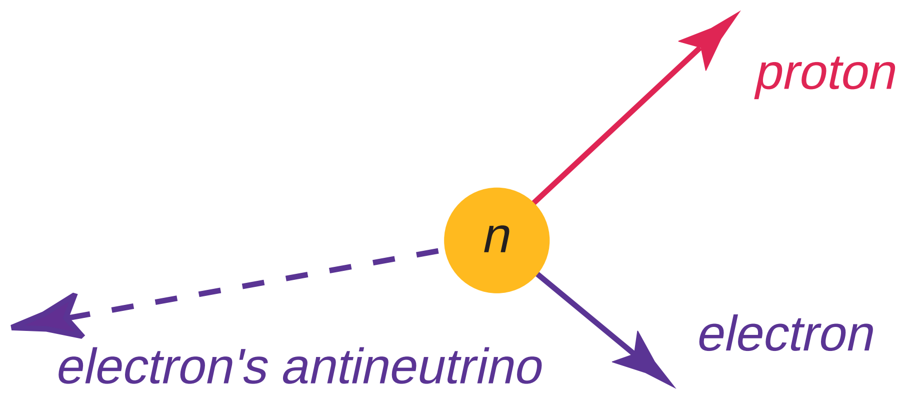
For the simpler case of neutron β decay, sometimes this happens:



A system initially at rest spontaneously moves off to the right!

Wolfgang Pauli's Proposal (1930)

The missing energy / momentum is carried away by a light neutral particle that goes undetected:



The (anti)neutrino!

$$\boxed{n \rightarrow \; p + \beta^{-} + \bar{\nu}}$$

Experimental Confirmation . . .

In 1953, Clyde Cowan and Fred Reines used the intense beam of antineutrinos from a fission reactor

$$^{A}\mathrm{Z} \to \; ^{A}(\mathrm{Z}+1) + \beta^{-} + \bar{\nu} \; ,$$

and a heavy target (10.7 ft^3 of liquid scintillator) containing about 10^{28} protons to detect the reaction

$$\bar{\nu} + p \to \; e^{+} + n \; .$$

The observation was confirmed and extended by their team in 1956.

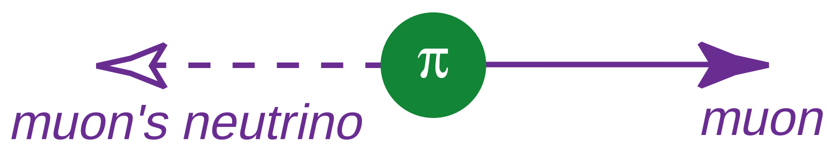
3 Families of Leptons

(Greek $\lambda\epsilon\pi\tau\acute{o}\varsigma$ = thin)

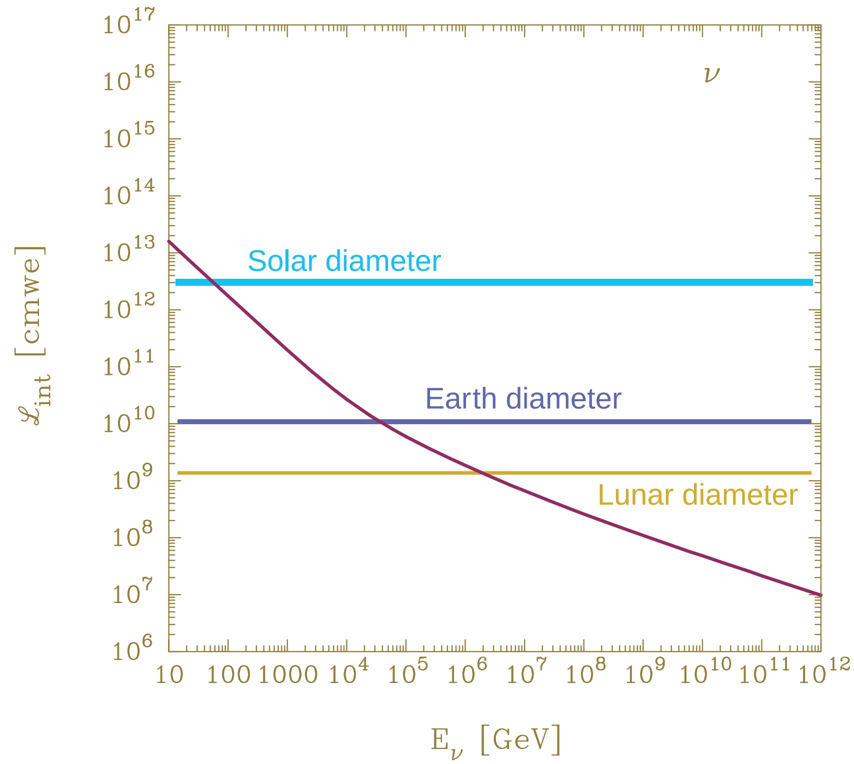
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Like the electron (+ muon + tau), the neutrinos have spin = 1/2.

The muon's neutrino is produced when the nuclear force particle, the pion, decays . . .



Neutrinos Traverse Vast Amounts of Material



Interaction Length of a 100-GeV $\nu = 25$ million km $H_2O \approx 230$ Earth diameters.

In Fermilab's neutrino beam, only 1 ν in 10^{11} will interact in your body.

Don't be neutrinos!

Consequences of the Great Interaction Length

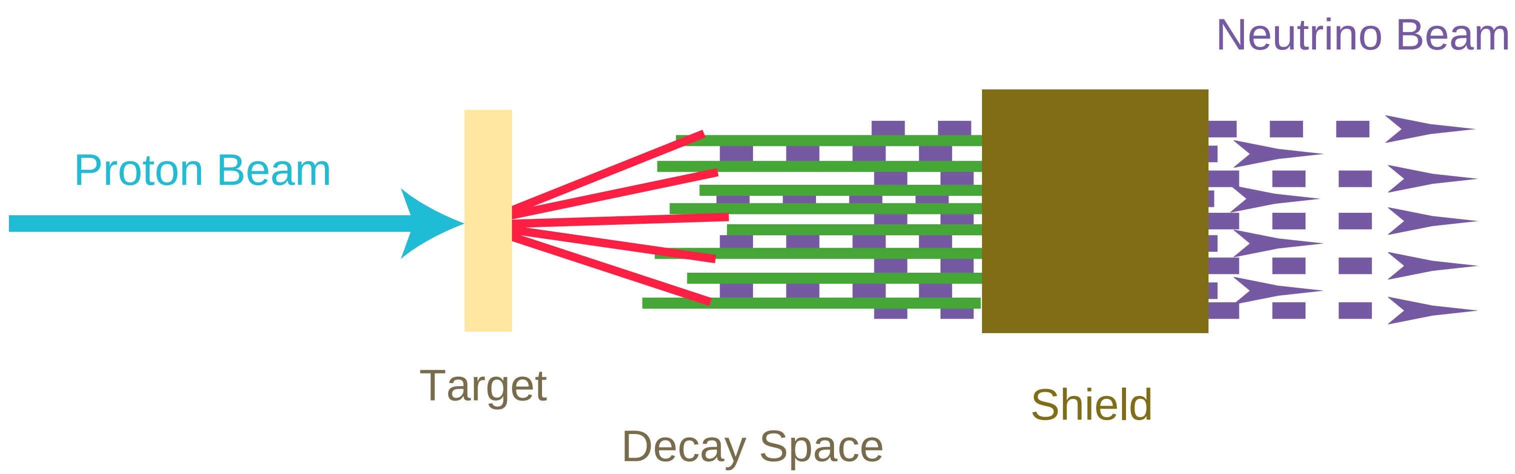
- Missing-energy signature for neutrinos
- Difficulty of detecting neutrino interactions
- Possibility of preparing filtered neutrino beams

How to Make a Neutrino Beam

$$p + \text{Target} \to \text{many } \pi,\ K$$

$$\pi \to \mu\nu_\mu, \quad K \to \mu\nu_\mu$$

Filter beam



(Fermilab beam lines)

Neutrinos Probe the Interior of the Proton

- Fermilab Tevatron delivers 10^{10} neutrinos in 5 pings over 2.5 seconds each minute, spread over the 100 ft^2 face of the NuTeV Detector.

- Detector is 690 T of iron, scintillator, and drift chambers. Events studied from "fiducial volume" of 390 T.

- The 10^{10} neutrinos produce about 10 – 20 events.

Experiments like this give us our best look at the interior of the proton, and reveal its quark structure in exquisite detail.

(NuTeV Detector and Collaboration)

Neutrinos Are Very Light

No one has ever weighed a neutrino.

Neutrino	Mass
ν_e	$< 0.000\,015$ MeV/c^2
ν_μ	< 0.17 MeV/c^2
ν_τ	< 18.2 MeV/c^2

electron mass is 0.51099907 MeV/c^2

If neutrinos are exactly massless neutrino physics is simple ...

- No pattern of masses to explain
- No neutrino decays
- No mixing among lepton generations
- No neutrino oscillations

The only question is Why?

In the Quantum World, Particles are Waves

If . . .

- Neutrinos $\nu_1, \nu_2, \ldots$ have different masses $m_1, m_2, \ldots$
- Each neutrino flavor is a mixture of different masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

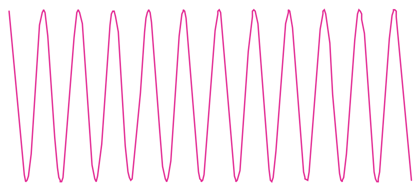
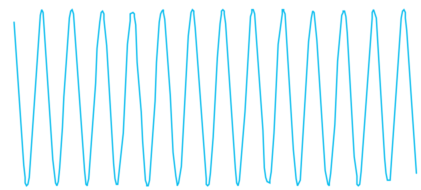
. . . then a beam born as pure ν_μ may evolve a ν_e component with time.

Probability that a neutrino born as ν_μ remain a ν_μ at distance L is

$$P_{\nu_\mu}(L) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2}{1 \text{ eV}^2} \cdot \frac{L}{1 \text{ km}} \cdot \frac{1 \text{ GeV}}{E} \right)$$

Neutrino Oscillation as an Interference Phenomenon

Two sound waves (two tuning forks with *almost* the same pitch)

 + 

Sound swells and fades periodically . . .

. . . because the two waves are different,

reflecting the physical difference between the two tuning forks.

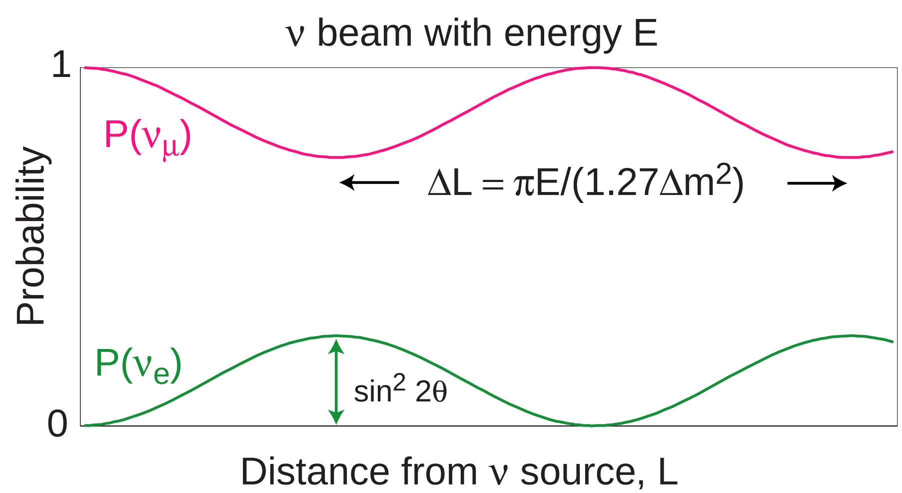
$$P_{\nu_e} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Depends on two experimental parameters:

- L, distance from ν source to detector [km]
- E, the neutrino energy [GeV]

...and two fundamental neutrino parameters:

- $\Delta m^2 = m_1^2 - m_2^2$ [eV^2]
- $\sin^2 2\theta$, the neutrino mixing parameter



Detecting Neutrinos from the Sun

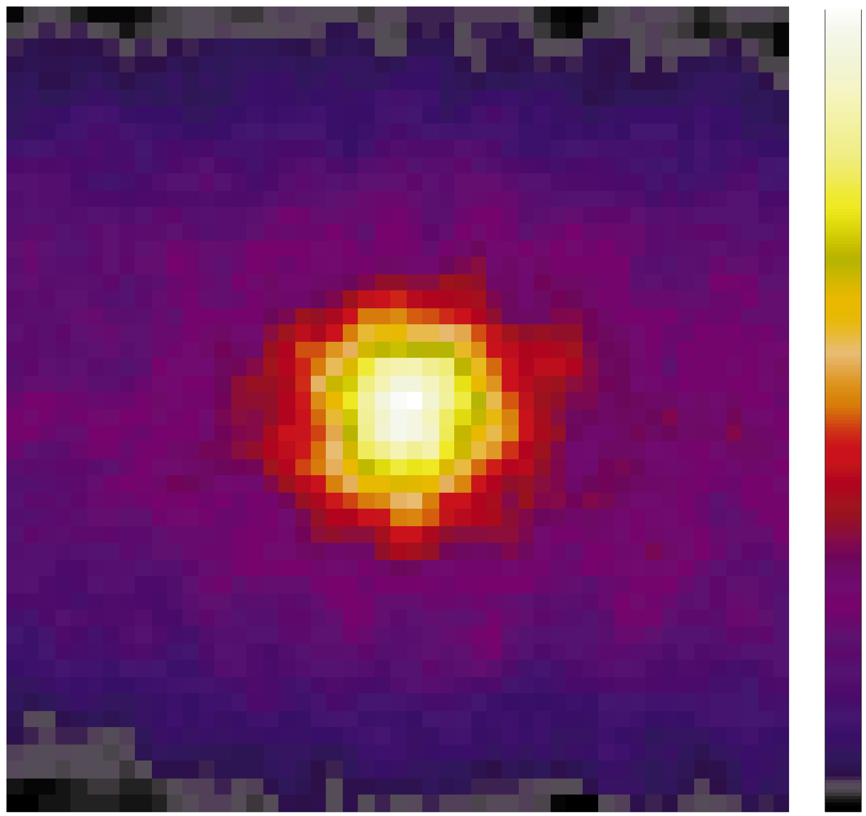
Neutrinos interact feebly $\Longrightarrow$ very massive target / detector.

SuperKamiokande Detector in Japan

- 50 000 tonnes of pure water
- 11 000 photomultiplier tubes to view Cherenkov light
- 1 km under a mountain, under 3 kmwe
- Detects neutrino interactions $\nu_e + n \to p + e^-$ in real time
- Determines the neutrino direction from the electron direction
- But is only sensitive to the highest-energy solar neutrinos

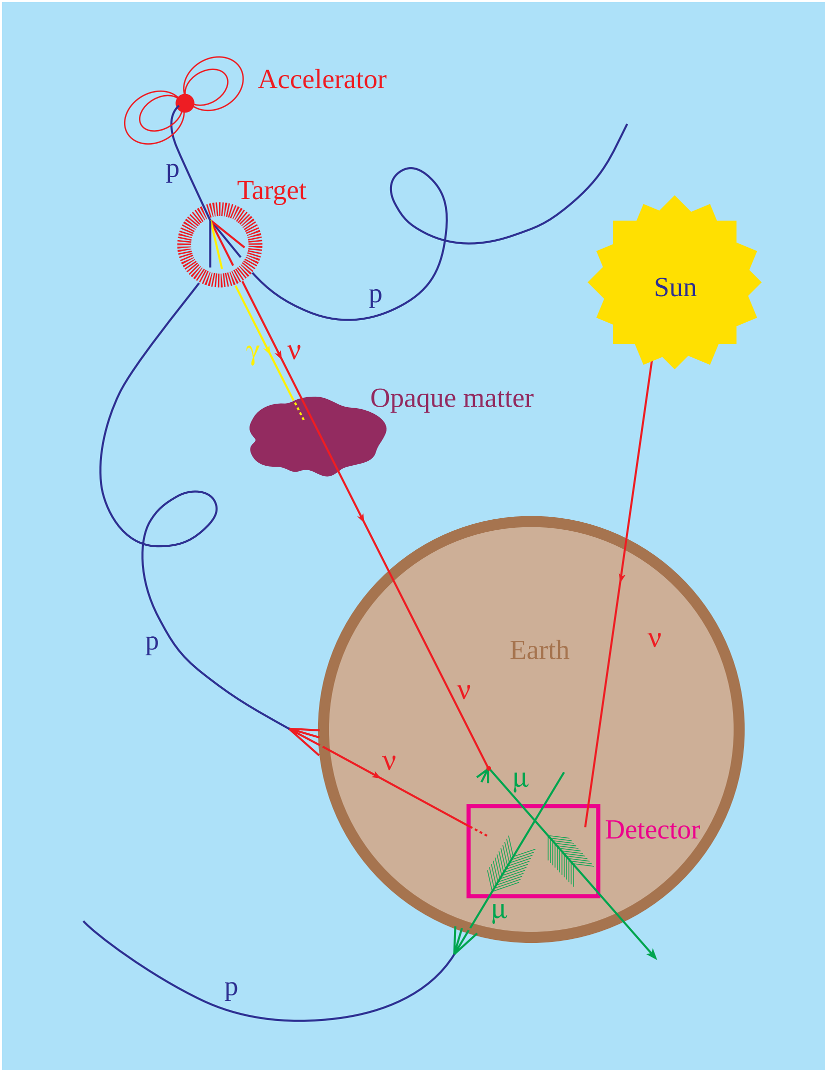
(SuperK Detector)

Brightest Object in the Neutrino Sky: the Sun



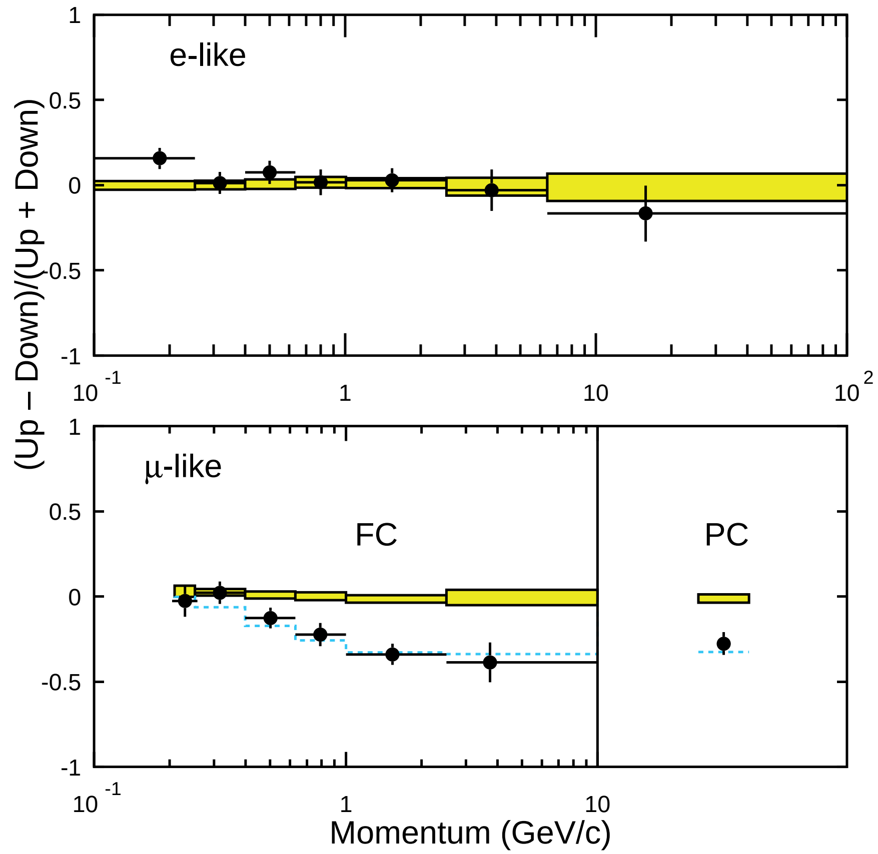
Proof that nuclear fusion powers the Sun.

Cosmic Rays Produce Neutrinos in the Atmosphere



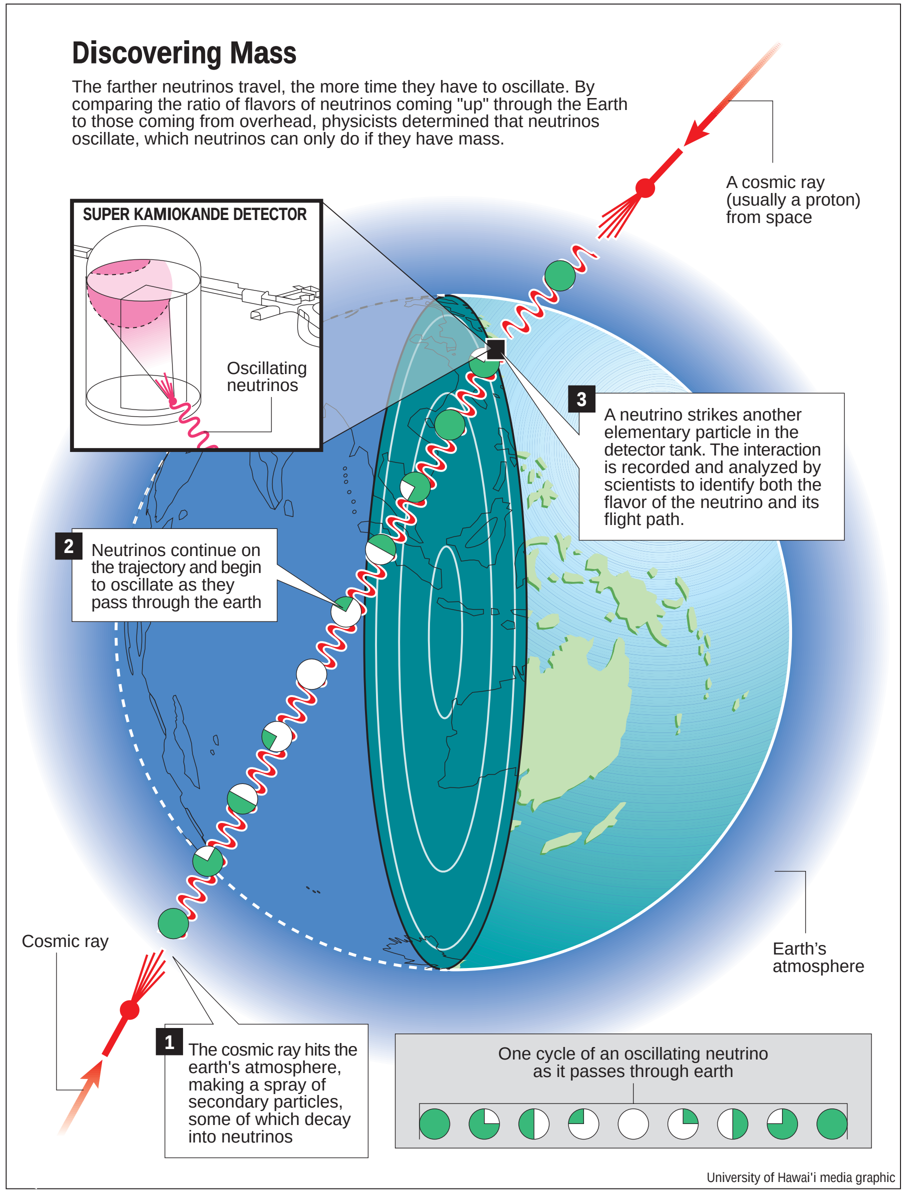
SuperK's Zenith-Angle Dependence

Downward ν travel about 15 km; upward ν travel up to 13 000 km



Upward ν_μ, which travel the longest path, are fewer than expected.

Oscillations?


Discovering Mass
The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.
SUPER KAMIOKANDE DETECTOR
Oscillating neutrinos
A cosmic ray (usually a proton) from space
3
A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.
2
Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth
Cosmic ray
Earth's atmosphere
1
The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos
One cycle of an oscillating neutrino as it passes through earth
University of Hawai'i media graphic

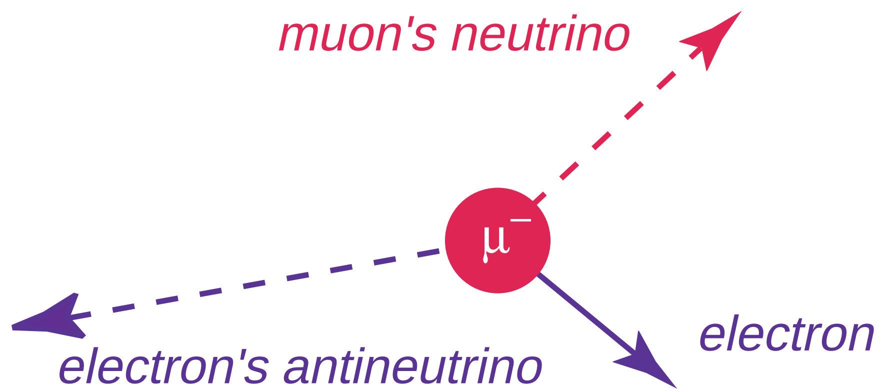
(New York *Times* article)

(MINOS Schematic)

The Ultimate Neutrino Source?

Muon storage ring with a millimole of muons per year.

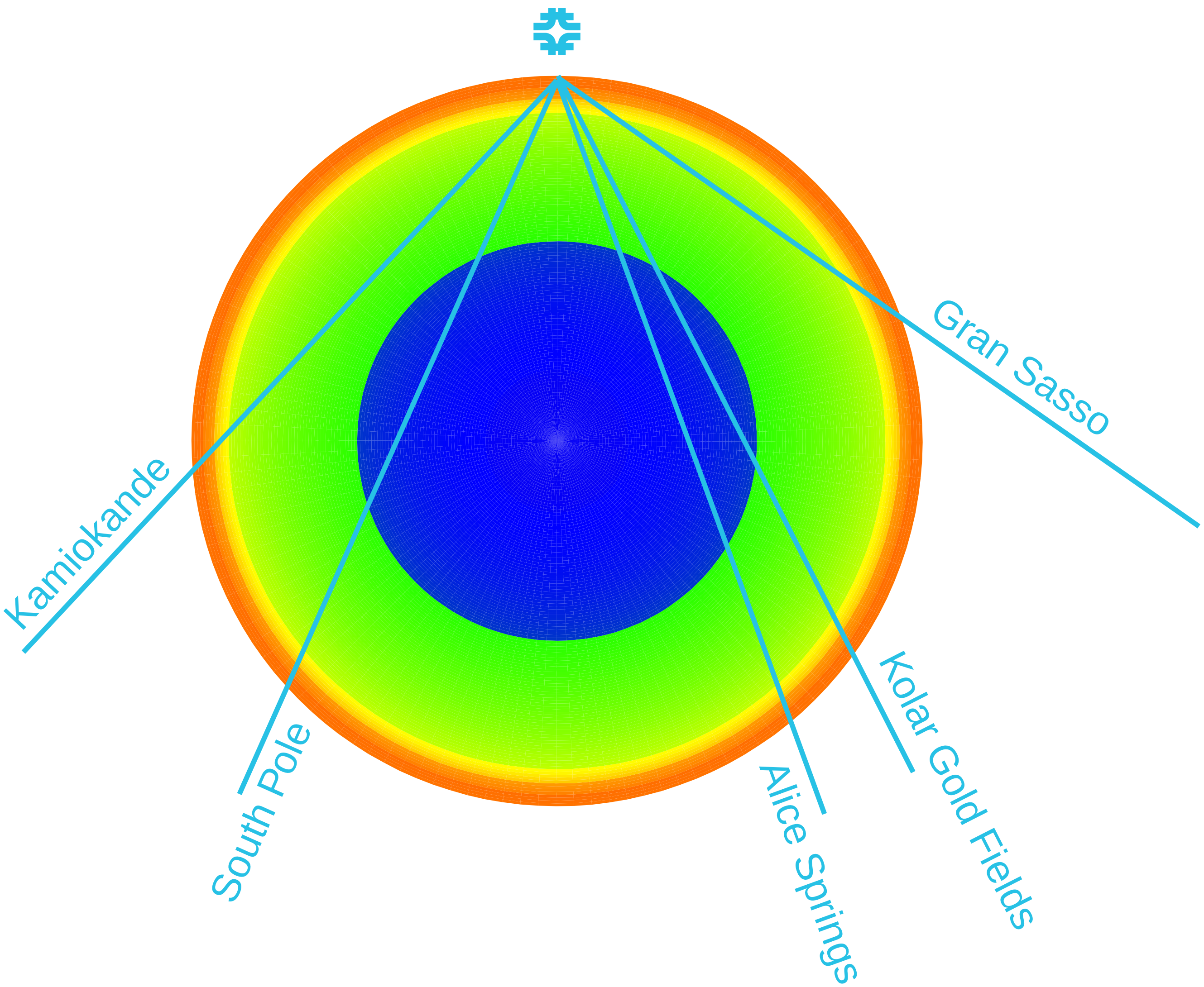
$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e \text{ OR } \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$



Racetrack 70 meters long holds 20-GeV muons. Point anywhere!

Replenish muons at 15 Hz.

The Ultimate International Collaboration?



The World's Most Powerful Microscope

Fermilab's Tevatron Collider and Its Detectors

900-GeV protons: $c - 364$ mph

1-TeV protons: $c - 295$ mph

Improvement: 69 mph!

Protons pass my window 45 000 times per second

(Tevatron + Main Injector)

***Physics Today:* CDF**

Physics Today: **DØ**

DØ Wins the Lottery!

(Postcard plot of $\sum E_T = 950$ GeV event)

(LEGO plot)

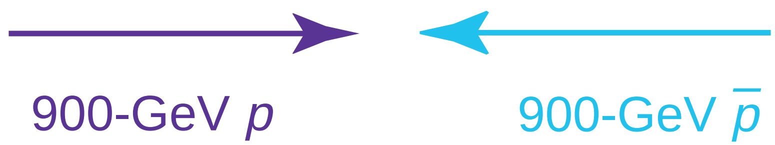
10^{-18} **m** $\approx 10^9 \times$ **size of an atom**

Do the quarks and leptons have structure?

What Can We Learn from the Top Quark?

- Top is an apparently elementary fermion with mass $\approx 175\ \mathrm{GeV}/c^2$ ($\approx$ gold atom) and charge $+2/3$.

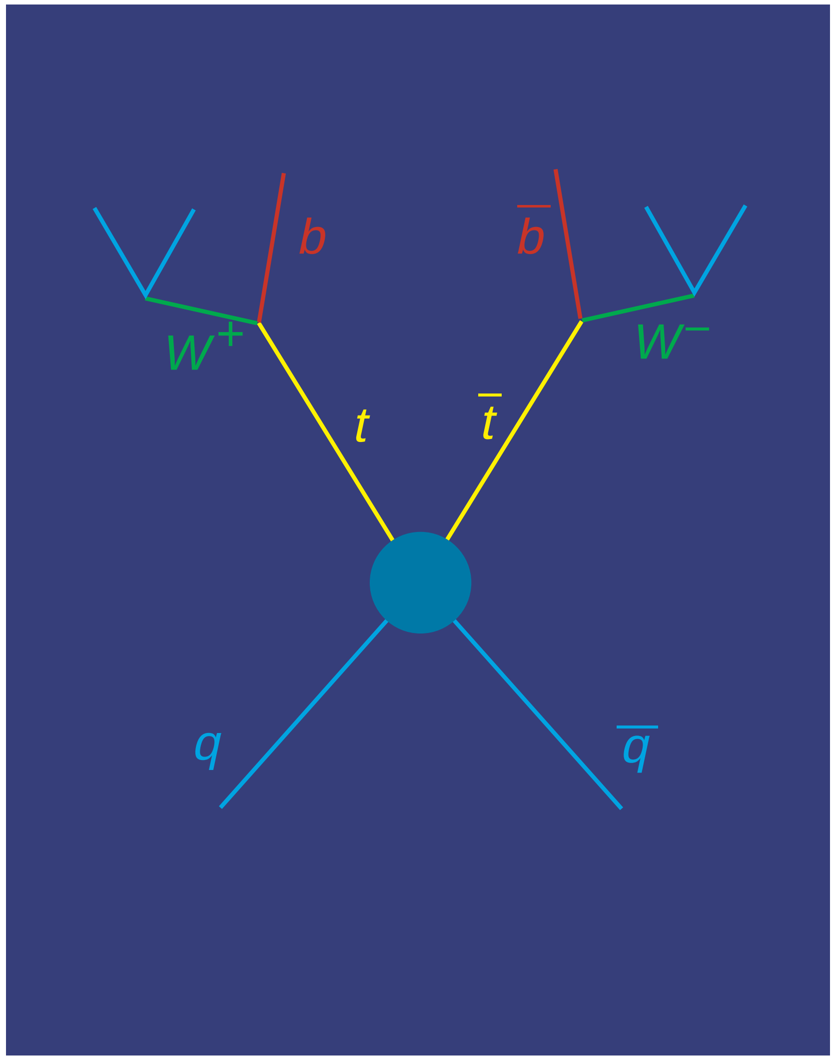
- For now, can only be produced in the Tevatron at Fermilab:



up to 10^6 collisions per second;
1 collision in 10^{10} produces a top-antitop pair

- Top's lifetime is $\approx 0.4 \times 10^{-24}$ second, yet it affects the everyday world

Full Professor's View of Top Production

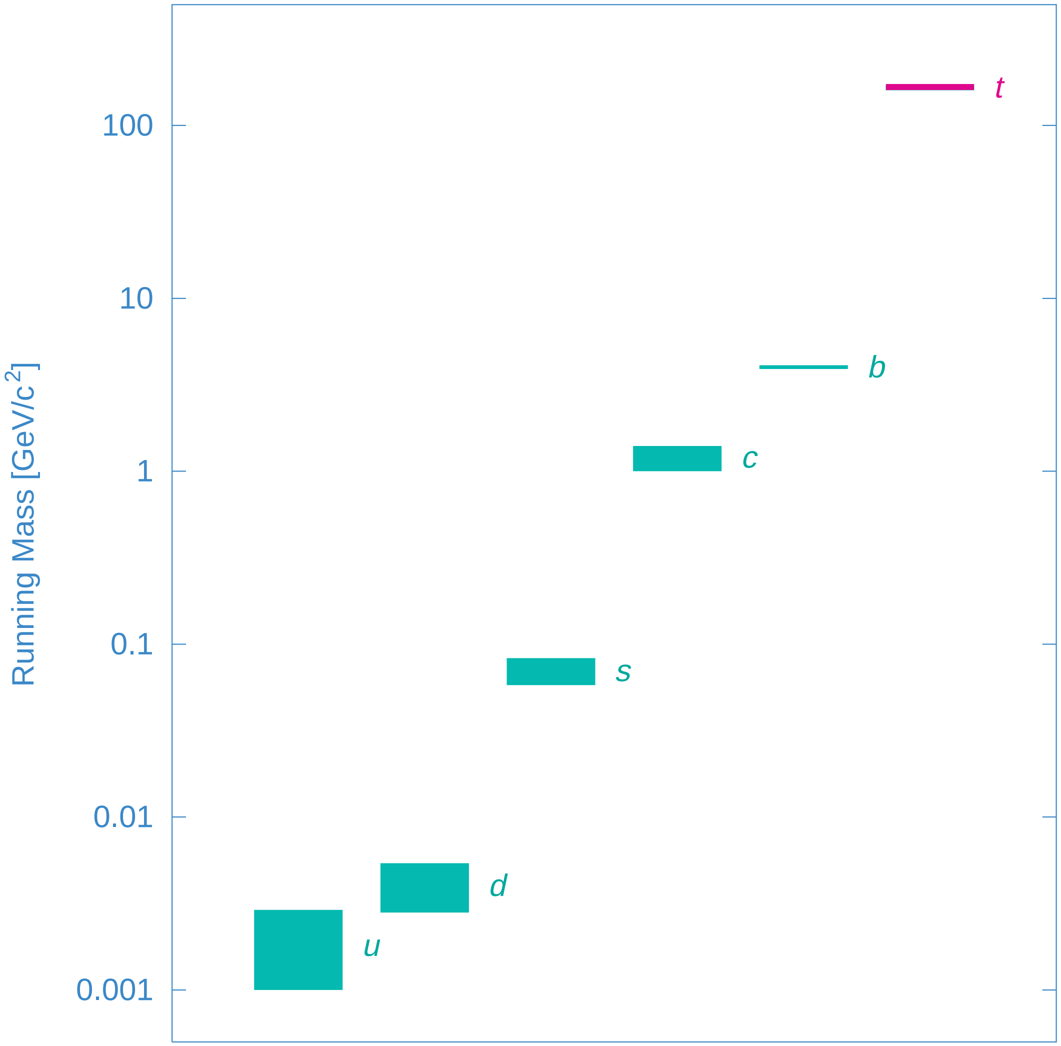


(Detector's View of Top Production)

(CDF Top Postcard)

(DØ Top Postcard)

Spectrum of Quark Masses



Three Families of Quarks and Leptons

	Quarks	Leptons
I	u (1963)	ν_e (1956)
	d (1963)	e (1897)
II	c (1974)	ν_μ (1962)
	s (1963)	μ (1947)
III	t (1995)	ν_τ
	b (1977)	τ (1975)

$\boxed{\text{The Problem of Identity:}}$

What makes a top quark a top quark and an electron an electron?

Is Nature Supersymmetric?

The flavor symmetry of the quark and lepton pairs,

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

is connected with the electroweak interaction.

The color symmetry of the quarks

$$\begin{pmatrix} u_R \\ u_G \\ u_B \end{pmatrix}$$

is connected with the strong interaction.

Constituents (fermions)	*vs.*	Force Carriers (bosons)
		γ
Pauli Principle		$W^{\pm},\ Z^0$
stability of matter		g

Can we unify fermions and bosons?

…constituents and force particles?

Fundamental Particles of the Standard Model and Their Superpartners

Particle	Spin	Color	Charge
g gluon	1	$\mathbf{8}$	0
$\tilde{g}$ gluino	1/2	$\mathbf{8}$	0
γ photon	1	$\mathbf{1}$	0
$\tilde{\gamma}$ photino	1/2	$\mathbf{1}$	0
$W^{\pm}$, Z^0 intermediate bosons	1	$\mathbf{1}$	$\pm 1, 0$
$\widetilde{W}^{\pm}$, $\tilde{Z}^0$ wino and zino	1/2	$\mathbf{1}$	$\pm 1, 0$
q quark	1/2	$\mathbf{3}$	$2/3, -1/3$
$\tilde{q}$ squark	0	$\mathbf{3}$	$2/3, -1/3$
e electron	1/2	$\mathbf{1}$	-1
$\tilde{e}$ selectron	0	$\mathbf{1}$	-1
ν neutrino	1/2	$\mathbf{1}$	0
$\tilde{\nu}$ sneutrino	0	$\mathbf{1}$	0
H^+, H^0, H'^0, H'^- Higgs bosons	0	$\mathbf{1}$	$\pm 1, 0$
$\tilde{H}^+, \tilde{H}^0, \tilde{H}'^0, \tilde{H}'^-$ Higgsinos	1/2	$\mathbf{1}$	$\pm 1, 0$

Supersymmetry must be broken (hidden), because $m_e \neq m_{\tilde{e}}$

Very provocative links with gravity and string theory
$\Longrightarrow$ Supersymmetry is likely to be true.

Issue: is it relevant to electroweak symmetry breaking?
Masses $\lesssim 1\ \mathrm{TeV}/c^2$, accessible to Run II

If bosons were the lightest constituents . . .

How Many Dimensions to Spacetime?

§ String theory requires 10-ish spacetime dimensions.

Assumed natural to take

$$R_{\text{unobserved}} \simeq 1/M_{\text{Planck}} \simeq 10^{-31}\ \text{cm}$$

What goes on there does affect the observable world: Excitations of tiny strings may determine spectrum of quarks and leptons.

§ New wrinkle

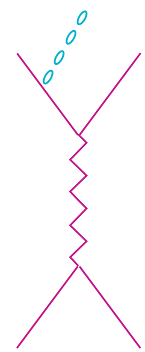
- Strong, weak, and electromagnetic interactions live on branes
- Gravity lives in the bulk (extra dimensions)

Could extra dimensions be quasimacroscopic?

If $M \sim 1\ \text{TeV}/c^2$, then $R \lesssim 1$ mm for ≥ 2 extra dimensions.

Remarkably, might have escaped detection ...

Examine real and virtual effects of **provatons:** GRAVITON EXCITATION OF TOWERS OF EXTRADIMENSIONAL MODES



New signatures, like

$$\begin{aligned} pp \quad &\rightarrow \quad \text{jet} + \not\!\!E_T \;\; (\text{parton} + \text{graviton}) \\ & \quad\quad \ell^+\ell^- + \not\!\!E_T \;\; (\ell^+\ell^- + \text{graviton}) \end{aligned}$$

Informative metaphor of collider as ultramicroscope

Are extra dimensions large enough to see?

provatons $< \; \pi\rho\acute{o}\beta\alpha\tau o$

(sheep, as in a flock)